Receptivity of Hypersonic Boundary Layers to Acoustic Disturbances

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NATO STO AVT-240 & RTG-082:
Hypersonic Boundary-Layer Transition Prediction
March 26, 2015

Objectives

- The physics based e^N correlation method (emalik^{3D}, LASTRAC, STABLE etc.) is easy to implement and yields satisfactory results if appropriate N-Factors are used to fix the transition onset. This factor depends on several parameters including geometry, tunnel noise and surface roughness. However, the N-Factors vary broadly and it becomes difficult to predict the onset accurately.

- Can we improve it? How can we achieve this?
- We have
  - **To include the effects of freestream disturbances on the transition process in the transition prediction methods**
  - **To identify a criterion to determine the transition onset point**

Results

- Show the results for
  - **Flow over a 7-deg cone at Mach 10. Experiments were performed recently in the T9 Tunnel.**
  - **Flow over a sharp and a blunt flared-cones at Mach 6. Experiments were performed in the Purdue Tunnel.**
  - **HIFiRE-1 Flight Experiment.**

Flow over a Cone at M=10 (Expts. Performed at T9, Marineau et al. AIAA 2014-3108)

Parameters

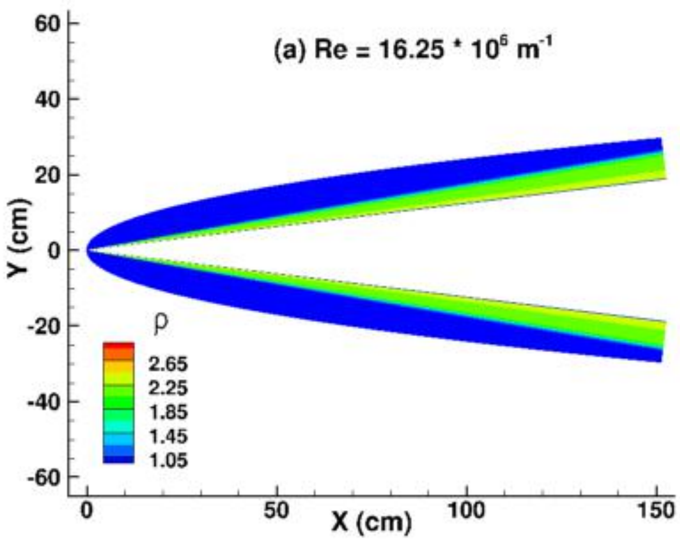
Case	R_n (mm)	P_o (MPa)	T_o (K)	M_∞	p_∞ (kPa)	T_∞ (K)	Re/m (1E6/m)
1 (3745)	0.152	2.3	982	9.39	82.34	52.69	2.03
2 (3743)	0.152	8.9	1018	9.60	275.15	52.38	7.03
3 (3742)	0.152	22.6	1035	9.86	584.97	50.62	16.25

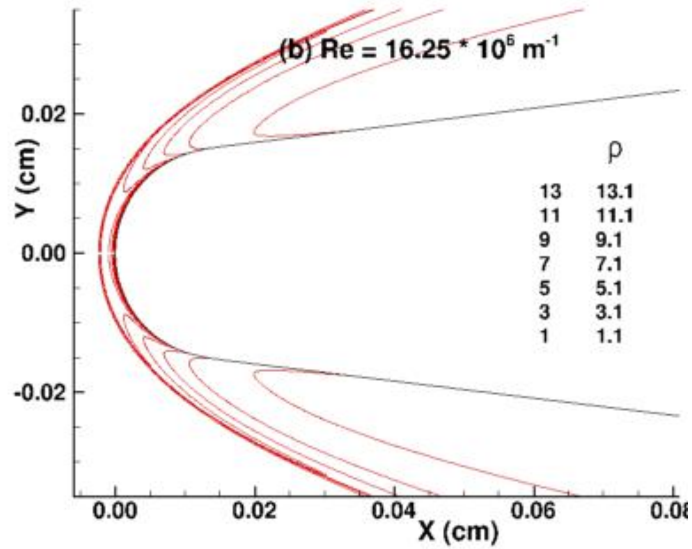
Cone half-angle = 7 deg.
$T_{wall} = 0.3^*T_o$
Pr = 0.74
γ = 1.4
Gas constant R = 297.

Sutherland viscosity law = $1.458^*10^{-6}\ T^{1.5} / (T+102.7\text{ K})$

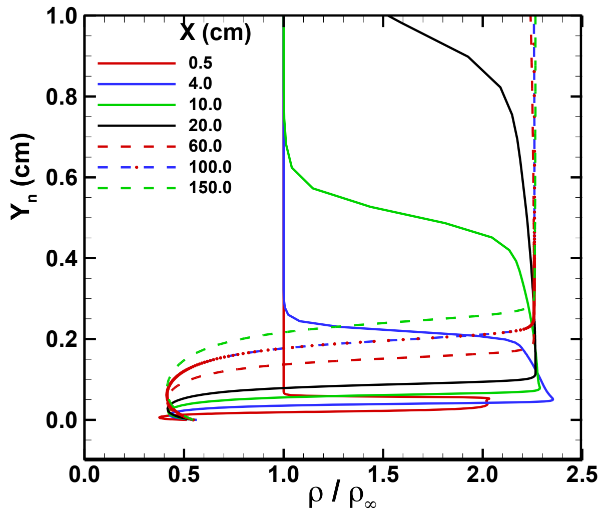
Leading edge of the cone: Sphere with radius, R_n

Mean Flow (Case 3)

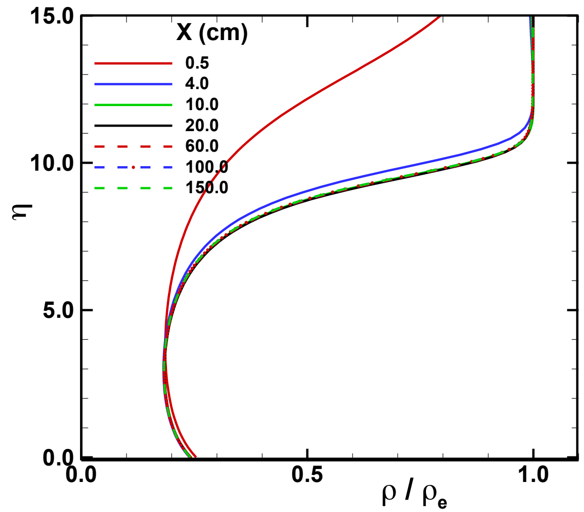




(a)

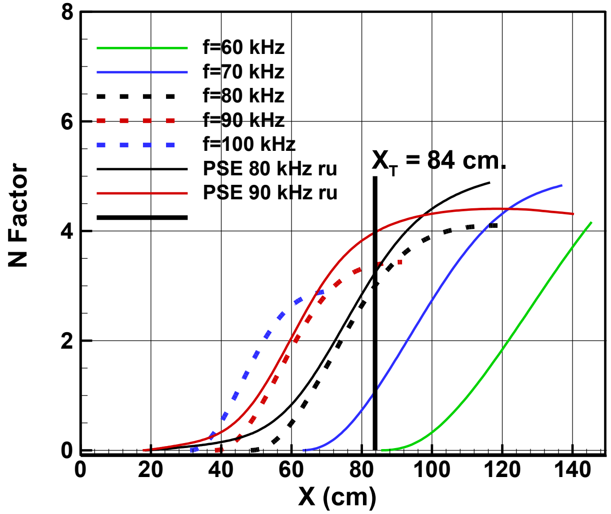


(b)

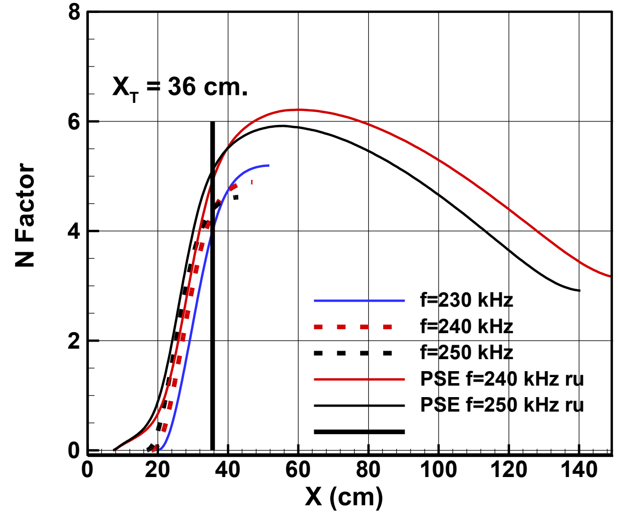


N-Factors (Cases 1-3)

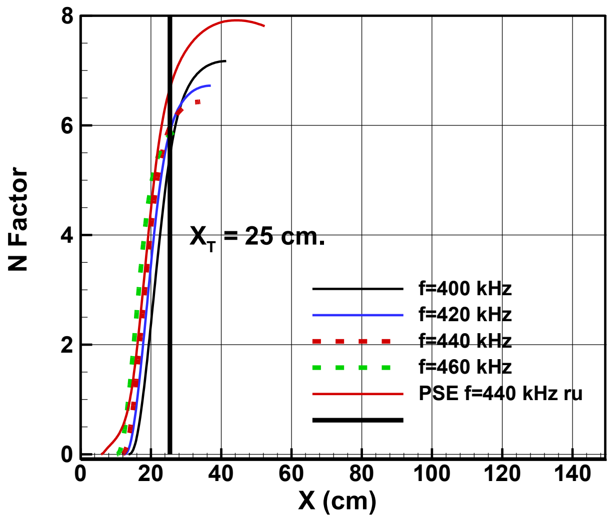
(a) Case 1



(b) Case 2



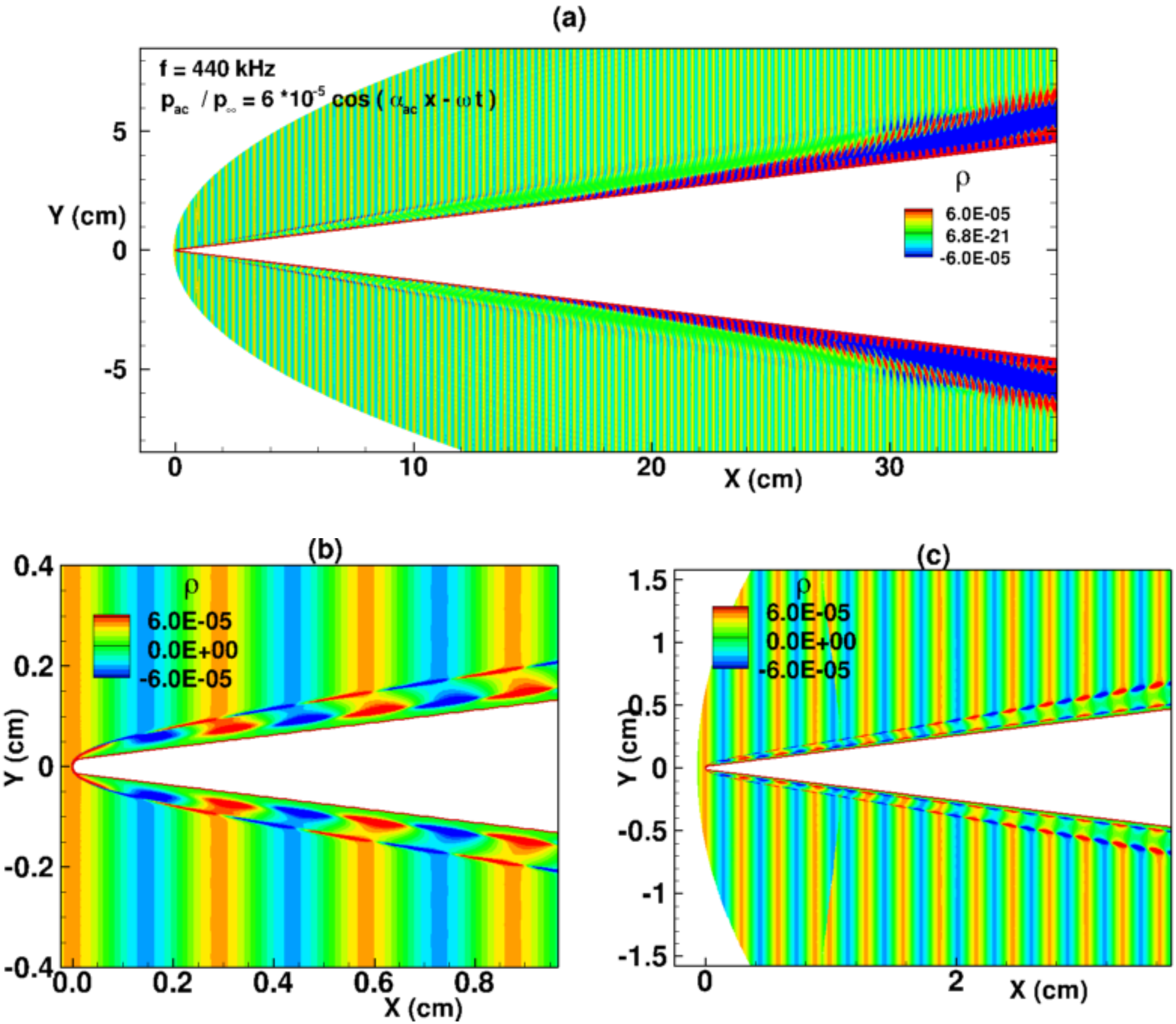
(c) Case 3



Transition Parameters

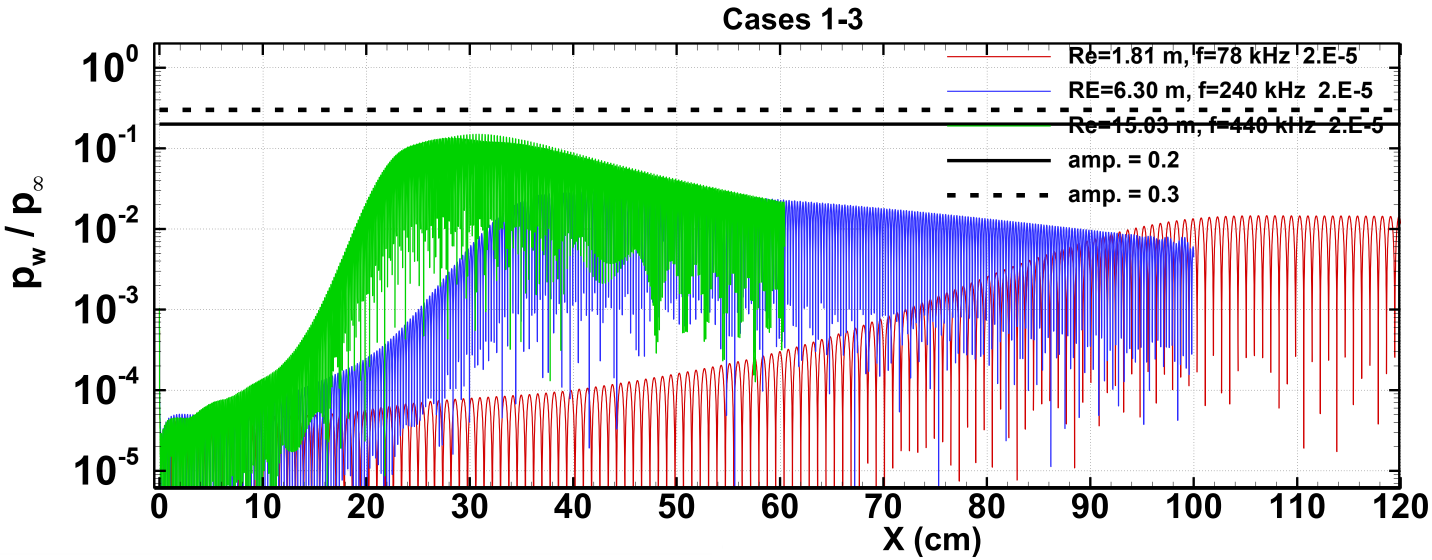
Case	R_n (mm)	Re/m (1E6/m)	S_T (m)	N	f (kHz)
1 (3745)	0.152	2.03	0.84	4.1	90
2 (3743)	0.152	7.03	0.36	5.1	240
3 (3742)	0.152	16.25	0.25	7.0	440

DNS



(a)
f = 440 kHz
$p_{ac} / p_\infty = 6 * 10^{-5} \cos(\alpha_{ac} x - \omega t)$
ρ
6.0E-05
6.8E-21
-6.0E-05
Y (cm)
X (cm)
(b)
ρ
6.0E-05
0.0E+00
-6.0E-05
Y (cm)
X (cm)
(c)
ρ
6.0E-05
0.0E+00
-6.0E-05
Y (cm)
X (cm)

DNS



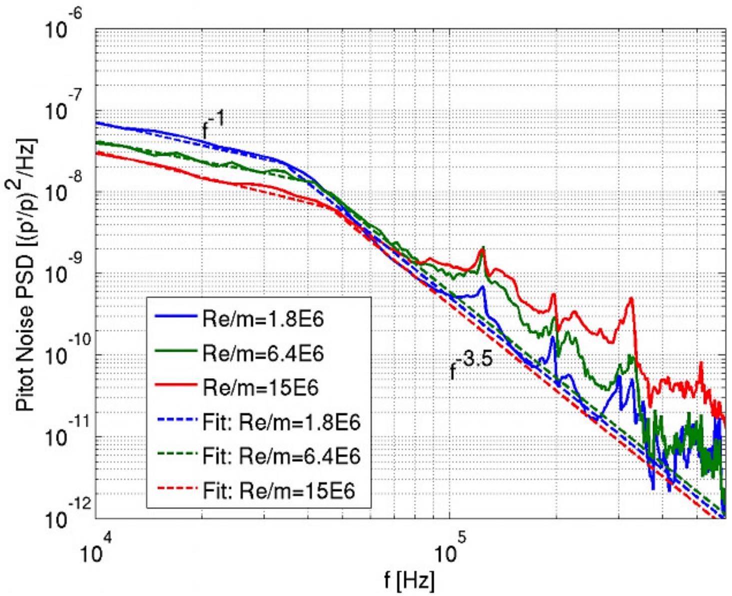


Fig. 18 PSD from expt. (Marineu et al. AIAA 2015)

$$p_{ac}(x,t) = \tilde{p}_{ac} e^{i(\alpha_{ac} x - \omega t)} + c.c,$$

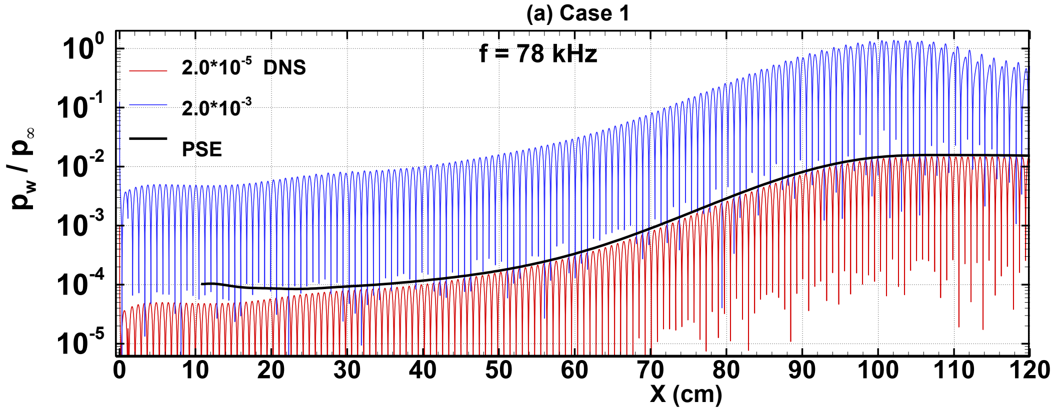
$$(p_{ac})_{PSD} = 2\left(\tilde{p}_{ac}\right)^2$$

Measured spectrum $\quad (p_{ac})_{PSD} = C \quad f^{-3.5} / Hz$

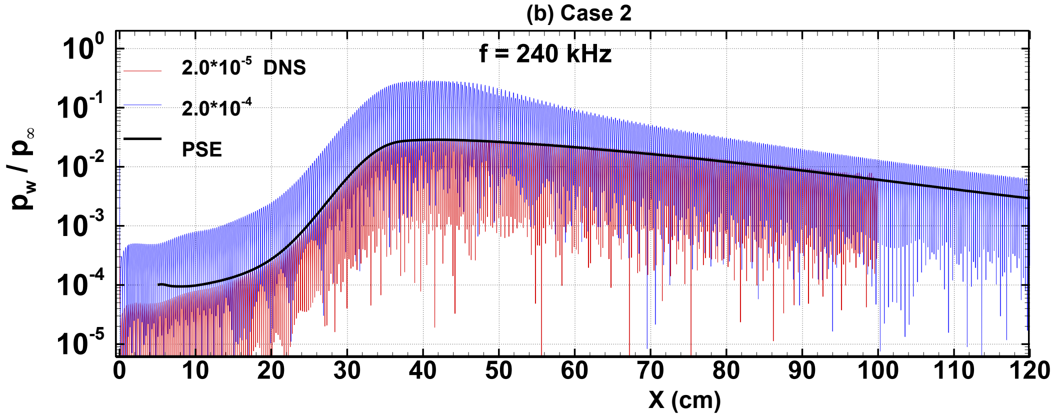
$$2\left(\tilde{p}_{ac}\right)^2 = C \quad f^{-3.5}\,\Delta f$$

$\Delta f \sim 10 \quad to \;\; 100\, kHz$ **(need to investigate more)**

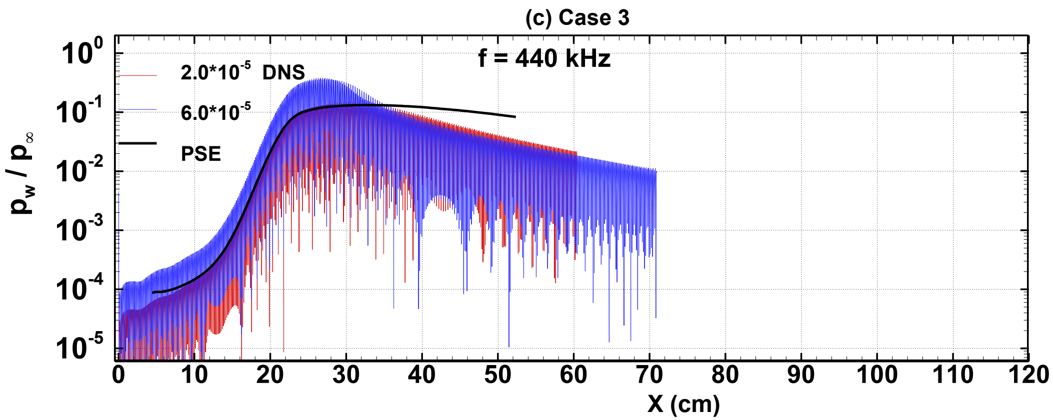
DNS



$$C_{recpt,p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$
$$= 2.0 \quad (x \sim 0)$$
$$= 4.5 \quad (x \sim 23\ cm)$$

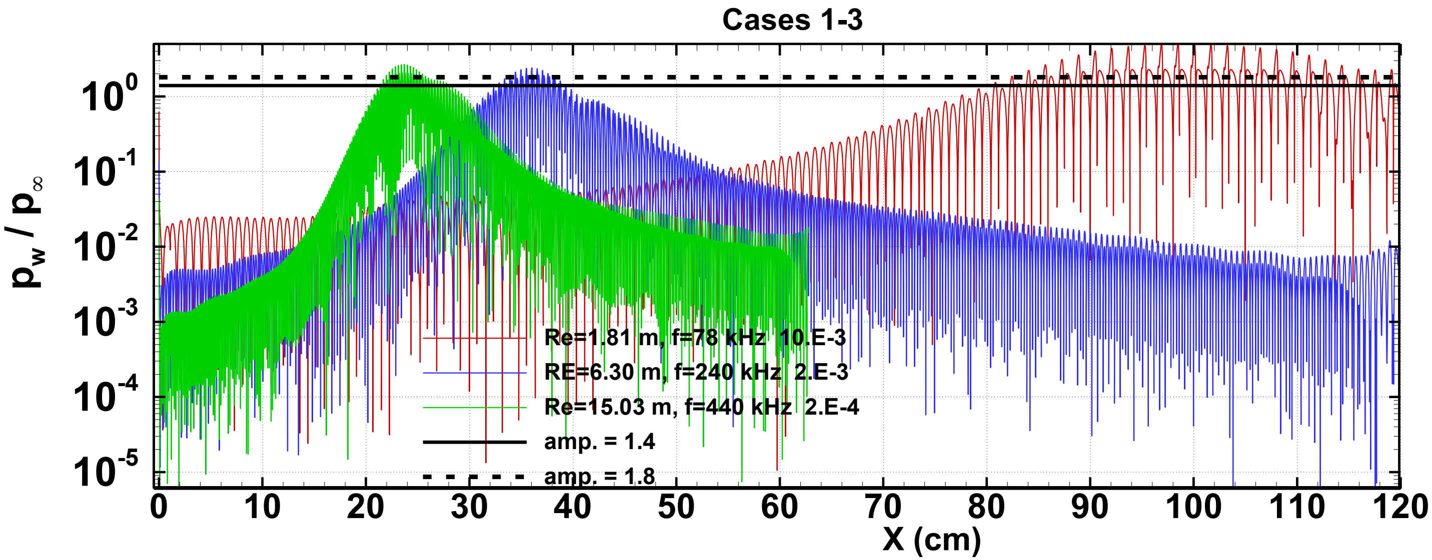


$$C_{recpt,p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$
$$= 2.0 \quad (x \sim 0)$$
$$= 5.0 \quad (x \sim 9\ cm)$$



$$C_{recpt,p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$
$$= 2.0 \quad (x \sim 0)$$
$$= 5.0 \quad (x \sim 5\ cm)$$

DNS



$$\frac{p_s}{p_\infty} = 3.29$$

Transition Onset

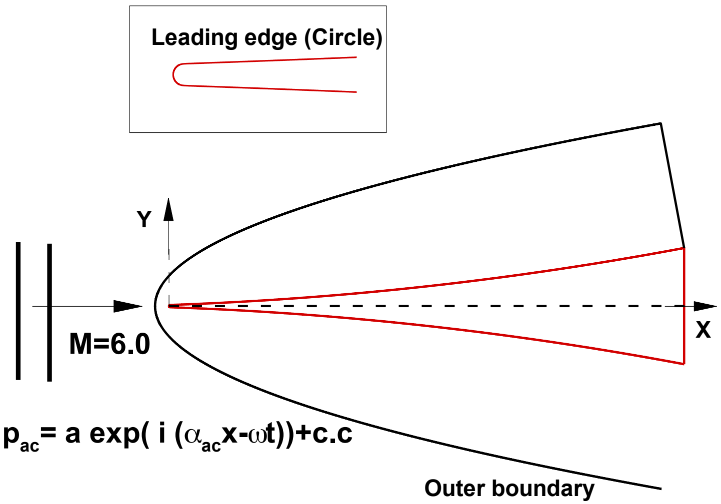
Case	X_T (cm)			N		
	$(p_{amp})_T$		Expt.	$(p_{amp})_T$		PSE
	1.4	1.8		1.4	1.8	
1	81	84	84	3.2	3.6	4.1
2	33	34	36	5.3	5.7	5.1
3	22	23	25	6.5	6.9	7.0

$$N_T = \frac{(p_{amp})_T}{C_{recpt, p_{wall}} \, p_{ac}}$$

Conclusions

- Transition onset points are predicted using the receptivity and a criteria based on the surface pressure.
- The criteria on the pressure has to be validated for other cases.
- The bandwidth for the amplitude calculations also has to be verified.
- Whether single frequency with equivalent amplitude or the multiple frequencies with small amplitudes is the right approach?

Mean Flow and Stability (Purdue Flared-Cones)



M_∞ = 6.0

Re = 10.3*10^6 m^{-1}

T_∞ = 52.80 ° K

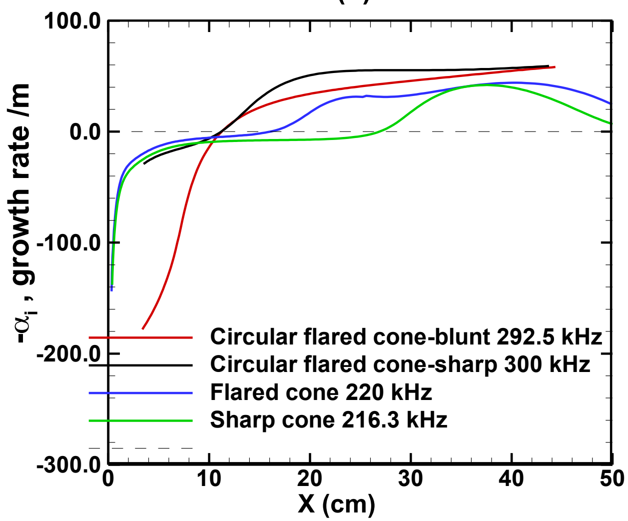
T_{wall}= 300.0° K

Leading edge radius r_0 = 0.16 , 1.0 mm

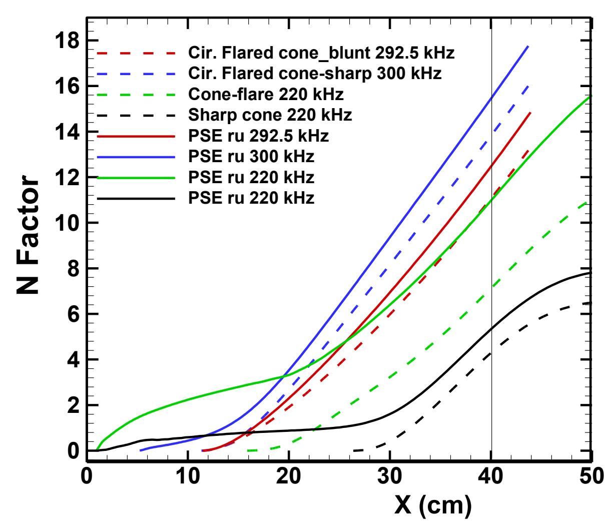
Flare is a circle with 3.0m radius

Slope is 2 degrees at the joint

(a)



(b)

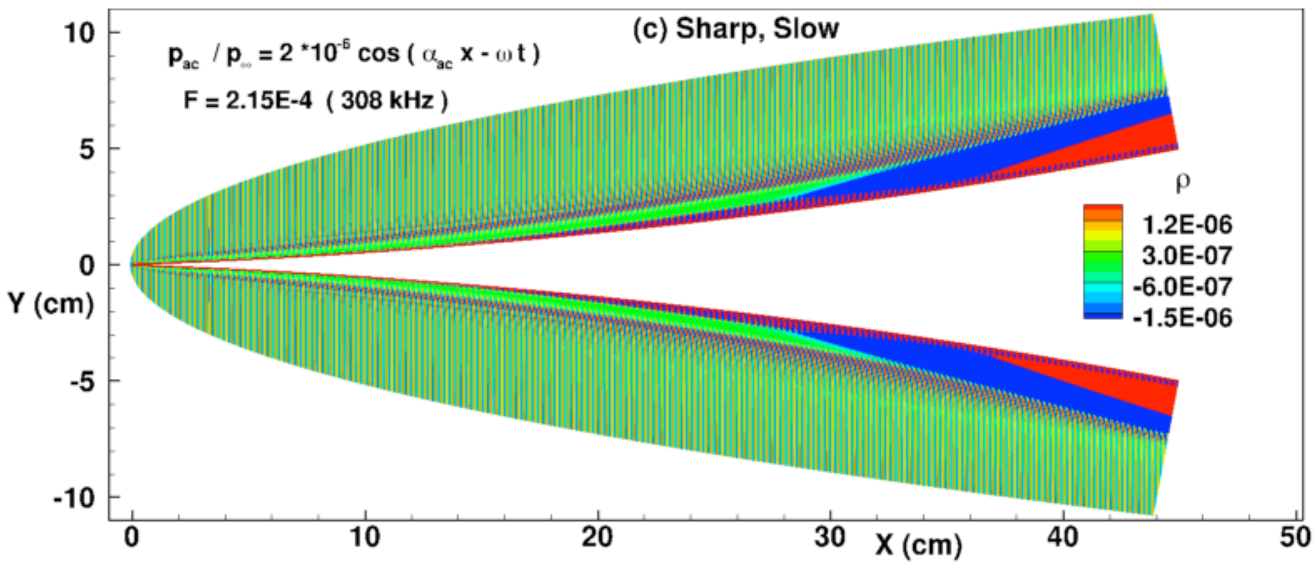


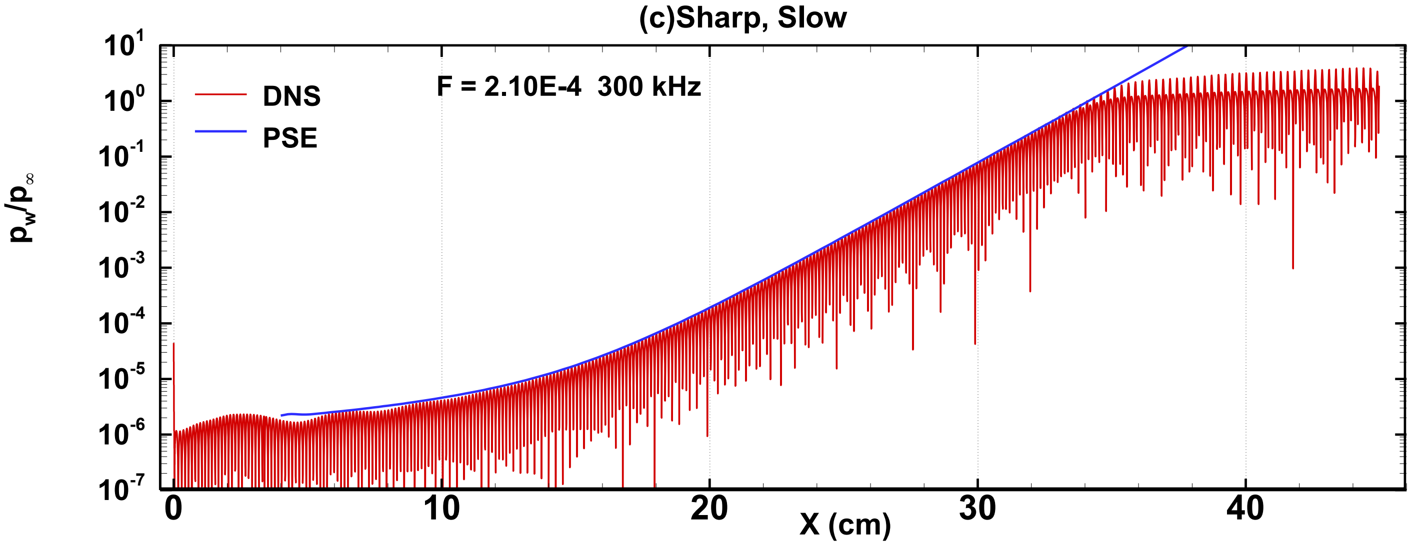
X = 40 cm

N=15 (sharp), 292 kHz

N=13 (Blunt), 300 kHz

DNS (Flared-Sharp-Cone)





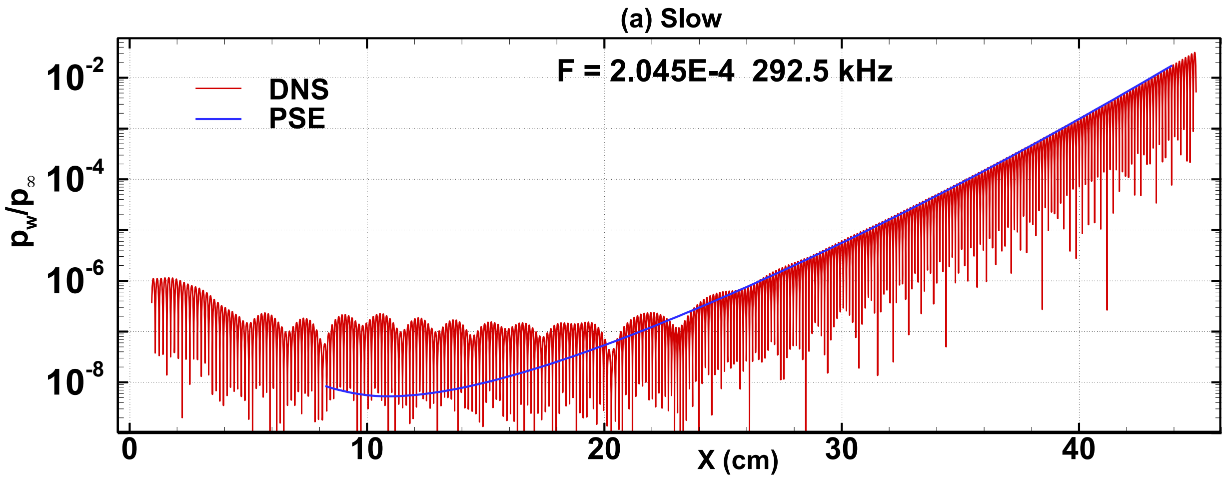
$$C_{recpt,p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$

$$= 1.0 \quad (x \sim 0)$$

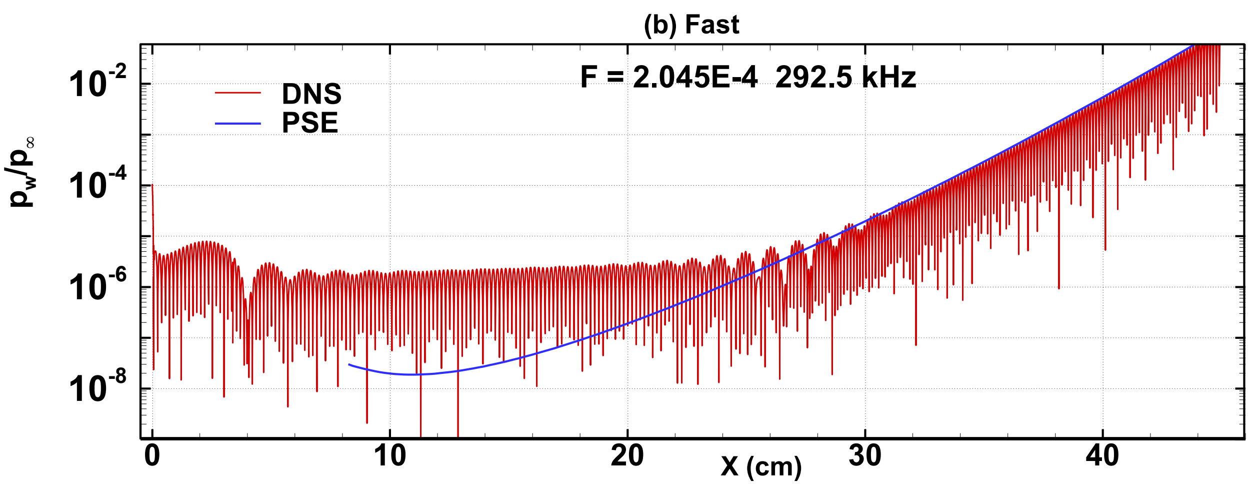
$$\frac{p_{wall}}{p_\infty} = 0.4 \quad (x \sim 33cm)$$

$$= 1.0 \quad (x \sim 36cm)$$

DNS (Flared-Blunt-Cone)

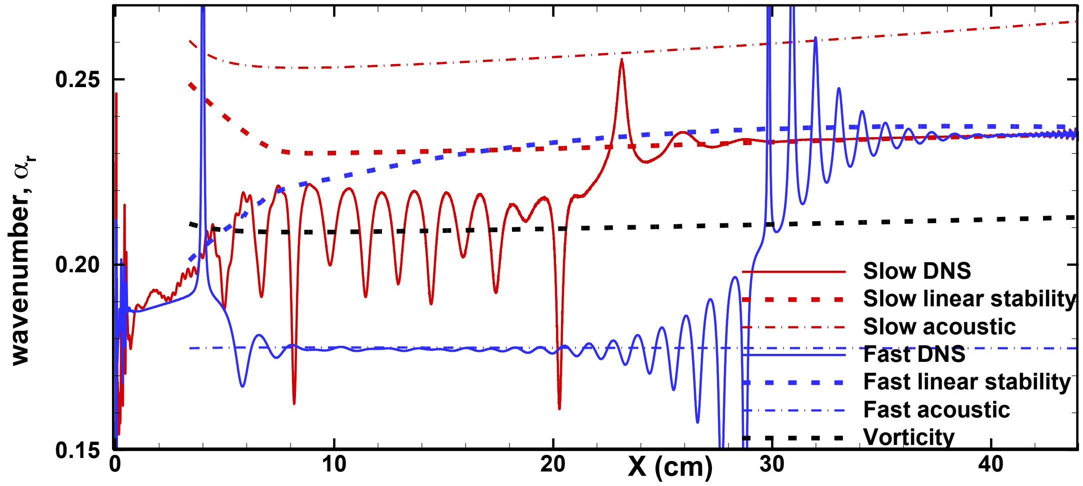


$$C_{recpt,p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$
$$= 5*10^{-3} \quad (x \sim 10cm)$$
$$\frac{p_{wall}}{p_\infty} = 0.0028 \quad (x \sim 40cm)$$

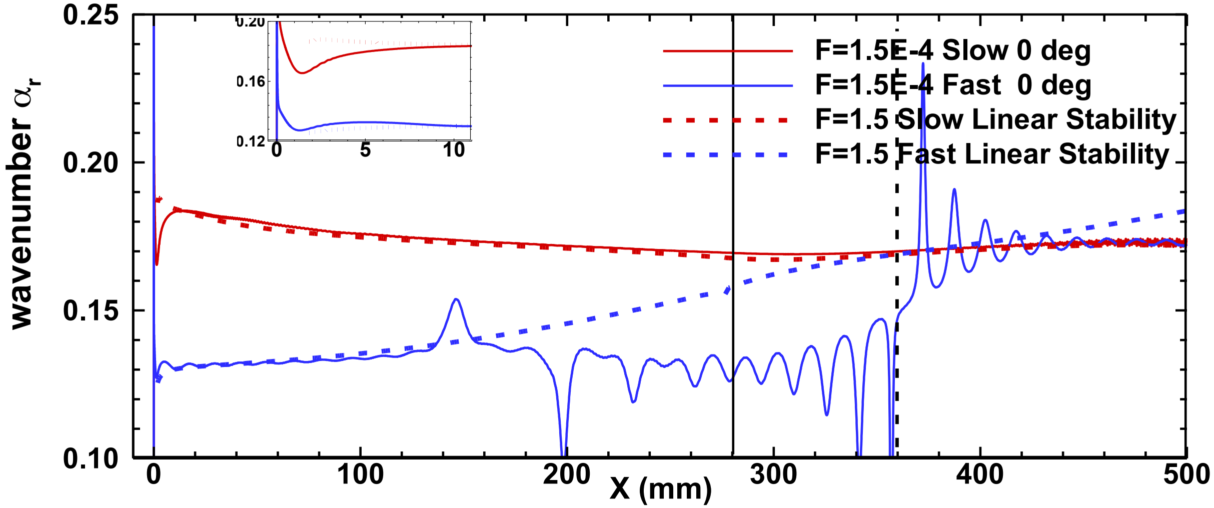


$$C_{recpt,p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$
$$= 10*10^{-3} \quad (x \sim 10cm)$$
$$\frac{p_{wall}}{p_\infty} = 0.0055 \quad (x \sim 40cm)$$

DNS (Flared-Blunt-Cone)

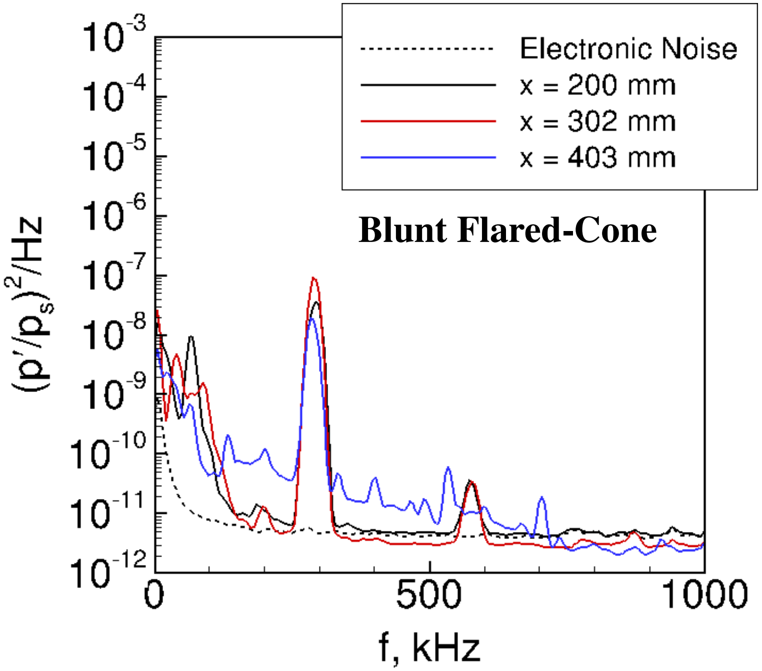


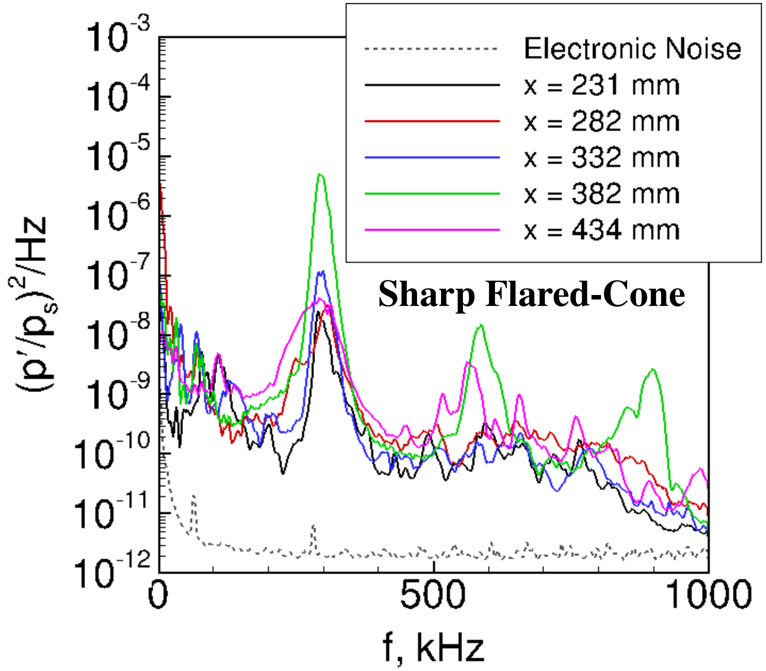
X ~ 22 cm (Slow)
X ~ 30 cm (Fast)

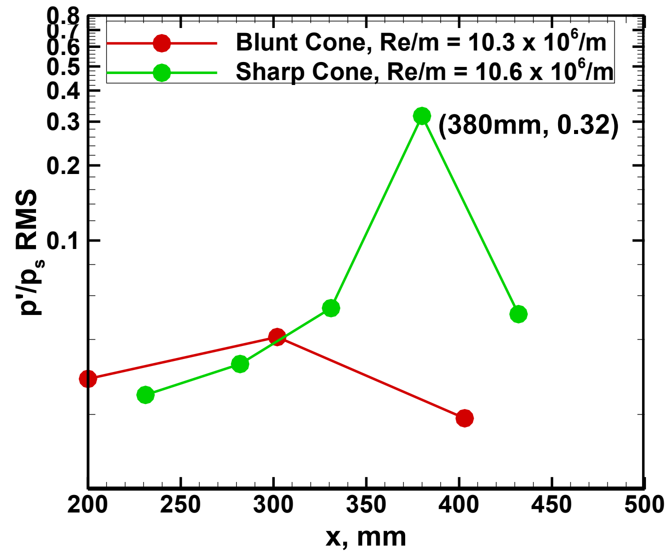


Straight sharp cone

Expts. (Flared-Sharp and Blunt-Cones)





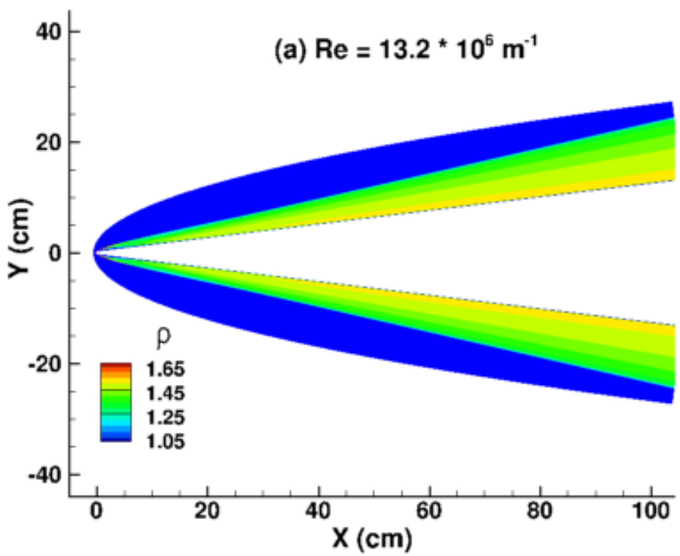


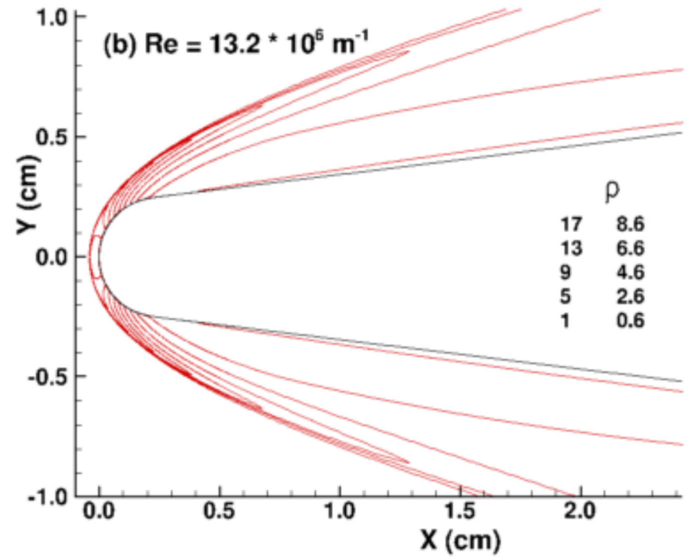
Amanda et al. AIAA-2015-1734

Conclusions

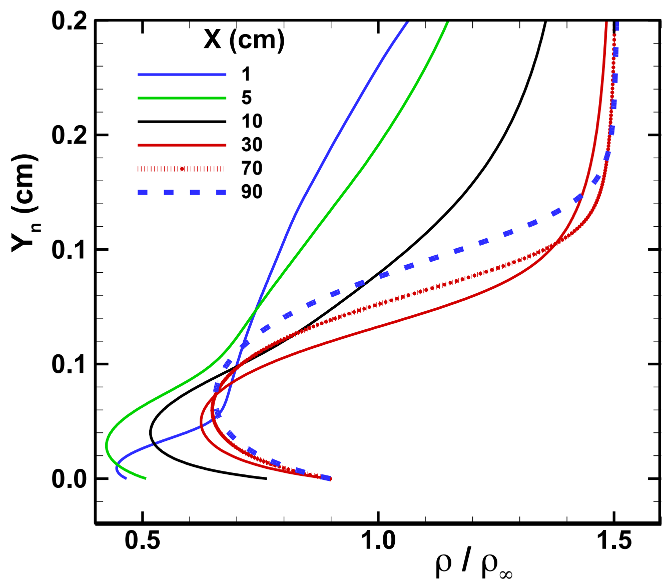
- A small bluntness affected the receptivity process over flared cones. Compared to the sharp flared-cone case, the receptivity coefficient is about 200 times smaller for the blunt flared-cone.
- These conclusions agree with the experimental data.

HIFiRE-1 (Kimmel et al. 2010) (t=21.5 sec)





(a)



T = 21.5 sec

Cone half-angle = 7 deg.

Nose radius = 2.5 mm (Re_n=33000)

Mach number = 5.3

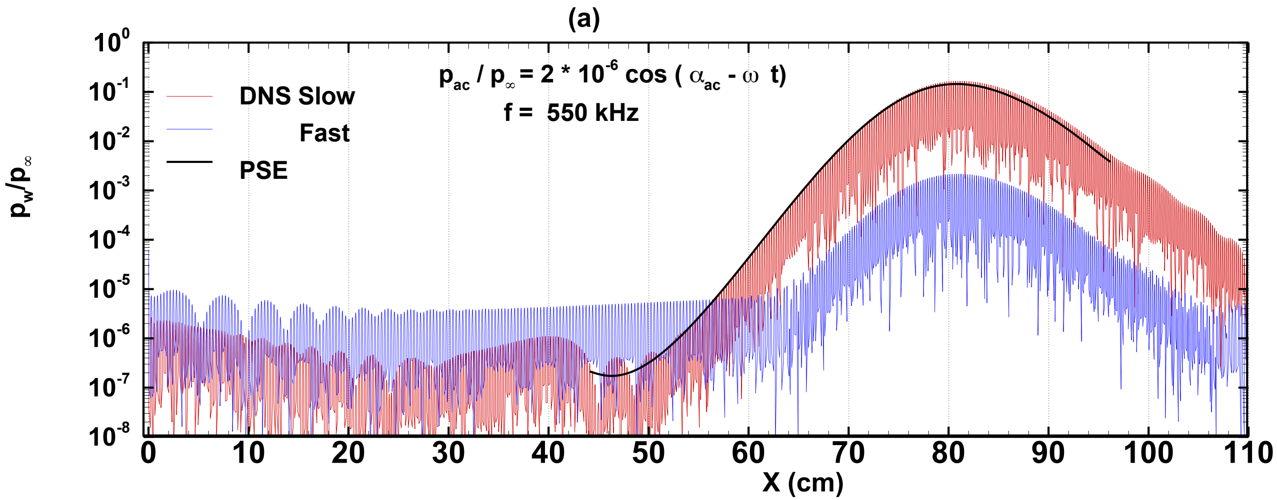
Freestream temp. = 201.4 K

Reynolds number = 13.2 *10^6/m

Transition onset = 0.805 m

Angle of attack = 0.0 deg

DNS (HIFiRE-1)



$$C_{recpt,p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$

$$= 1 * 10^{-1} \quad (x \sim 47cm)$$

$$\frac{p_{wall}}{p_\infty} = 2.0 * 10^{-7} \quad (x \sim 47cm)$$

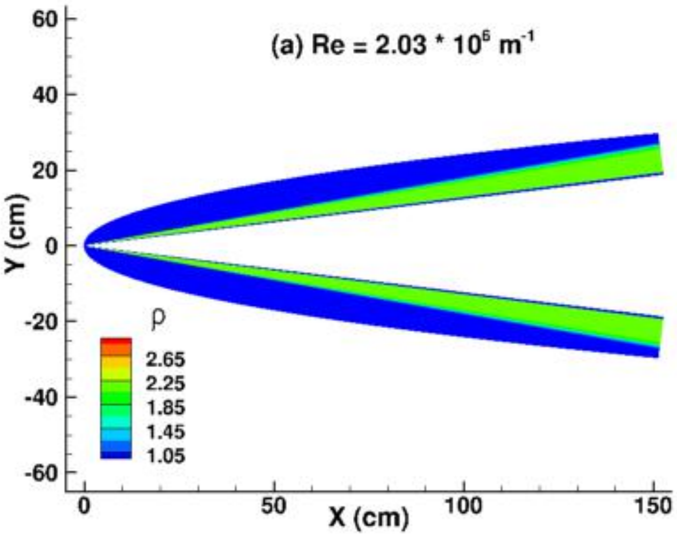
$$\frac{\left(p_{wall}\right)_{\max}}{p_\infty} = 0.17 \quad (x \sim 80cm)$$

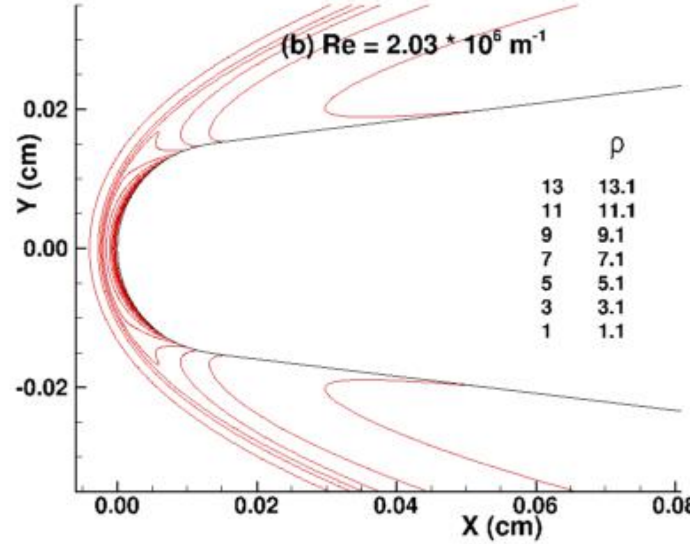
$$N - Factor = 13.8$$

Conclusions

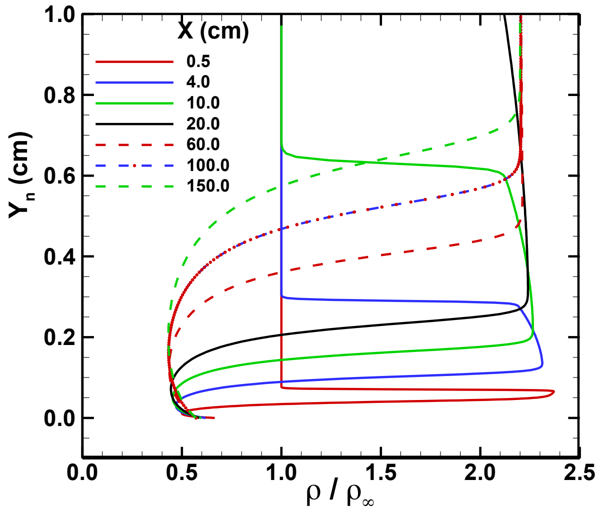
- Cooling and bluntness stabilized the first mode. The disturbances started to grow from x ~ 50 cm.
- Maximum amplitude reached with the free stream acoustic level of ($1.*10^{-6}$) is 0.17. At the transition onset it should be ~ 1.4.

Mean Flow (Case 1)

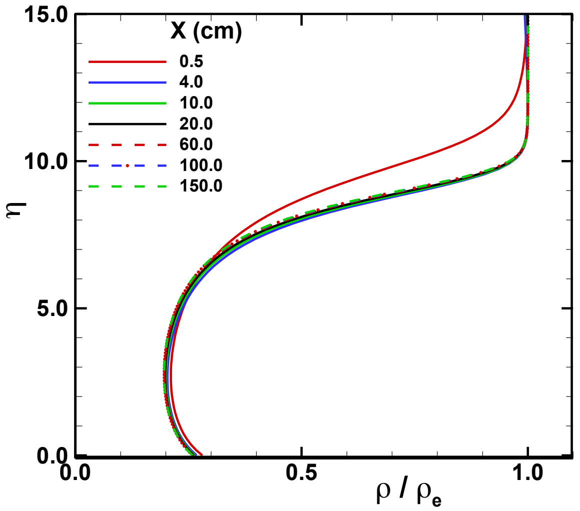




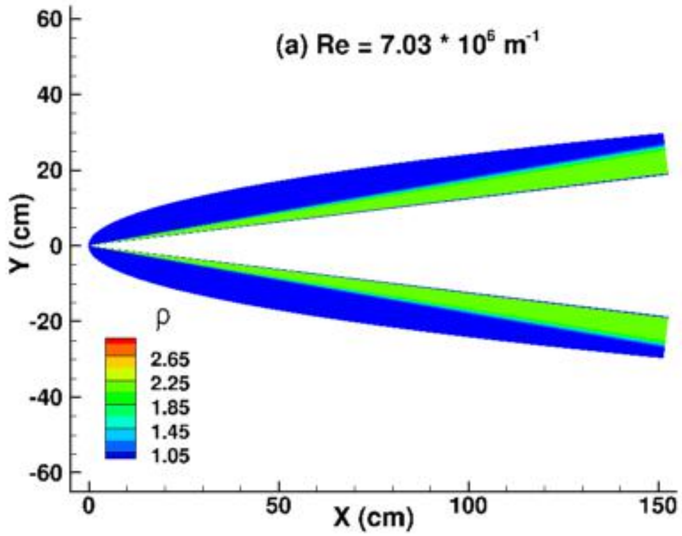
(a)

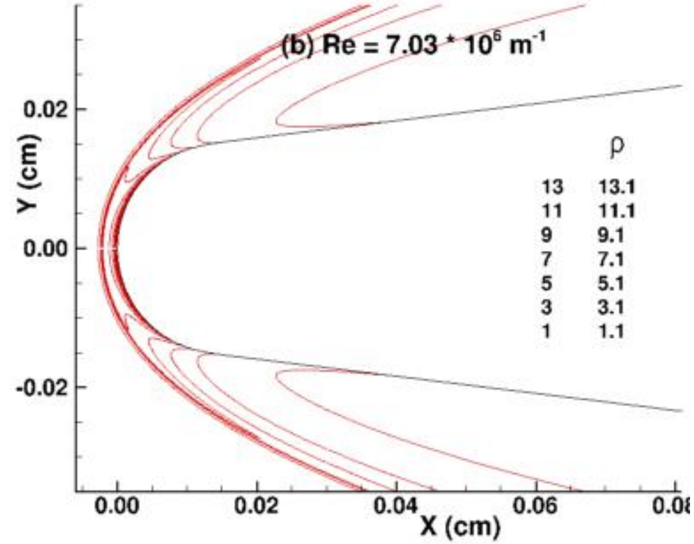


(b)

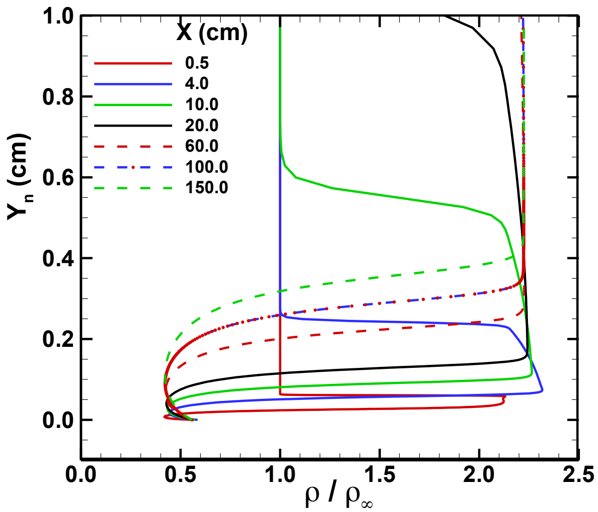


Mean Flow (Case 2)

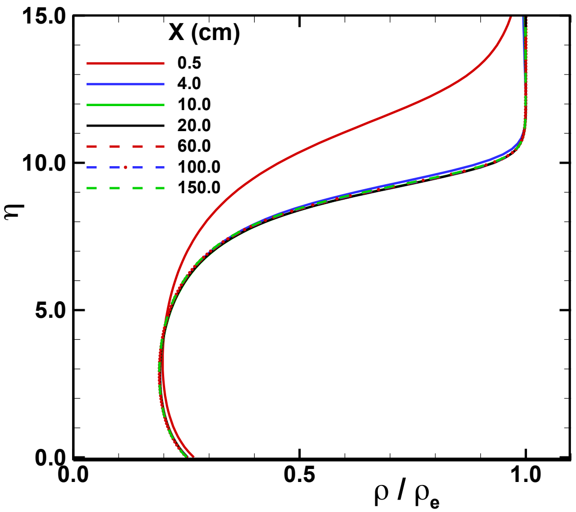




(a)



(b)



DNS

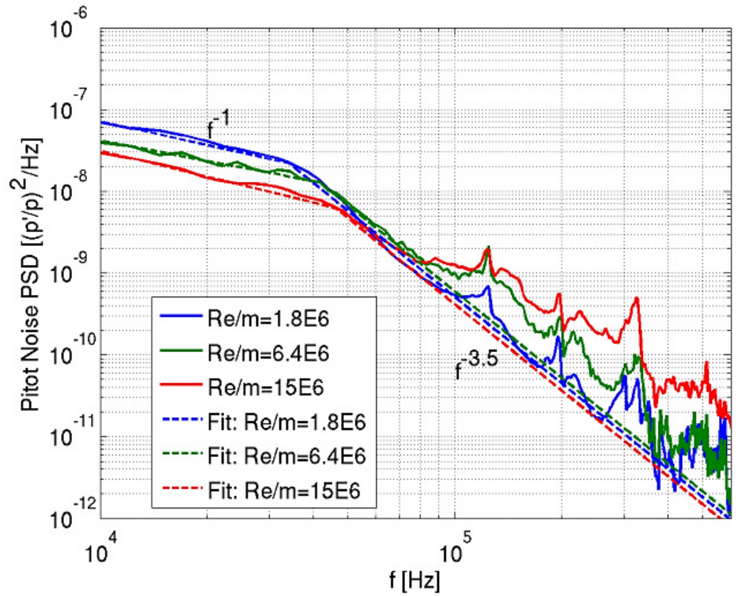


Fig. 18 PSD from expt. (Marineu et al. AIAA 2015)

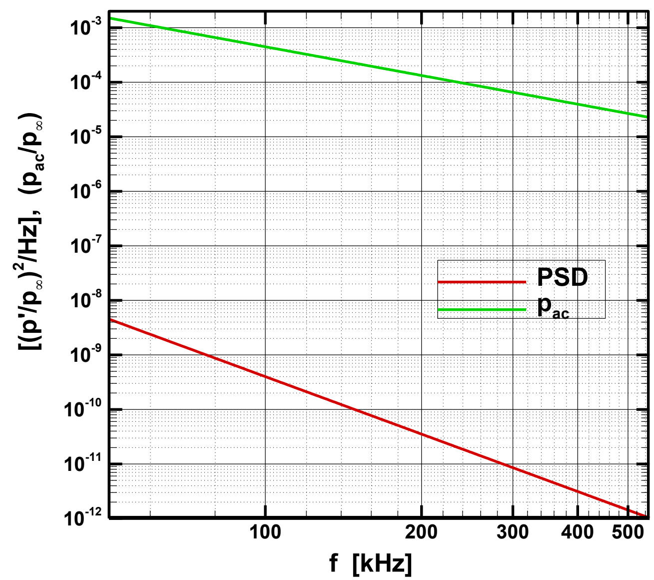
$$p_{ac}(x,t) = \tilde{p}_{ac} e^{i(\alpha_{ac} x - \omega t)} + c.c,$$

$$(p_{ac})_{PSD} = 2\left(\tilde{p}_{ac}\right)^2$$

Measured spectrum $(p_{ac})_{PSD} = C \quad f^{-3.5} / Hz$

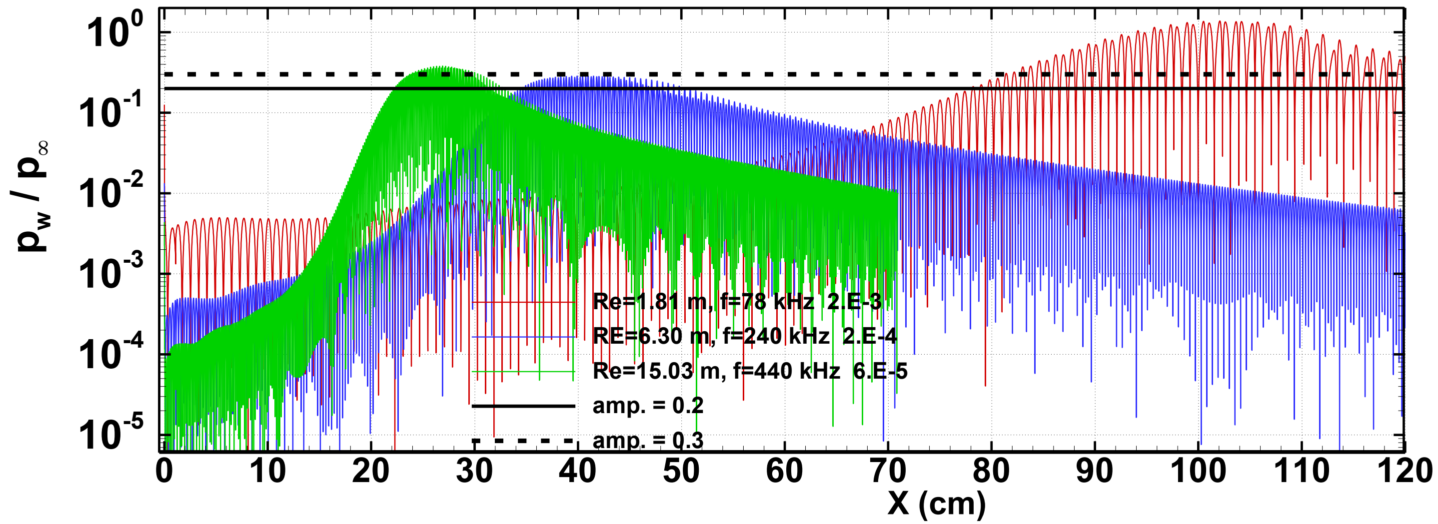
$$2\left(\tilde{p}_{ac}\right)^2 = C \quad f^{-3.5}\ \Delta f$$

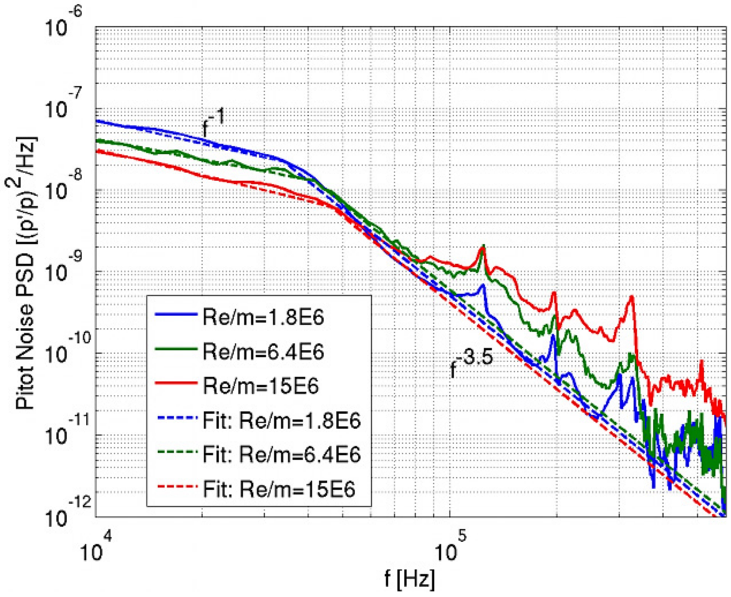
$\Delta f \sim 10 \quad to\ \ 100\ kHz$ **(need to investigate more)**



DNS

Cases 1-3





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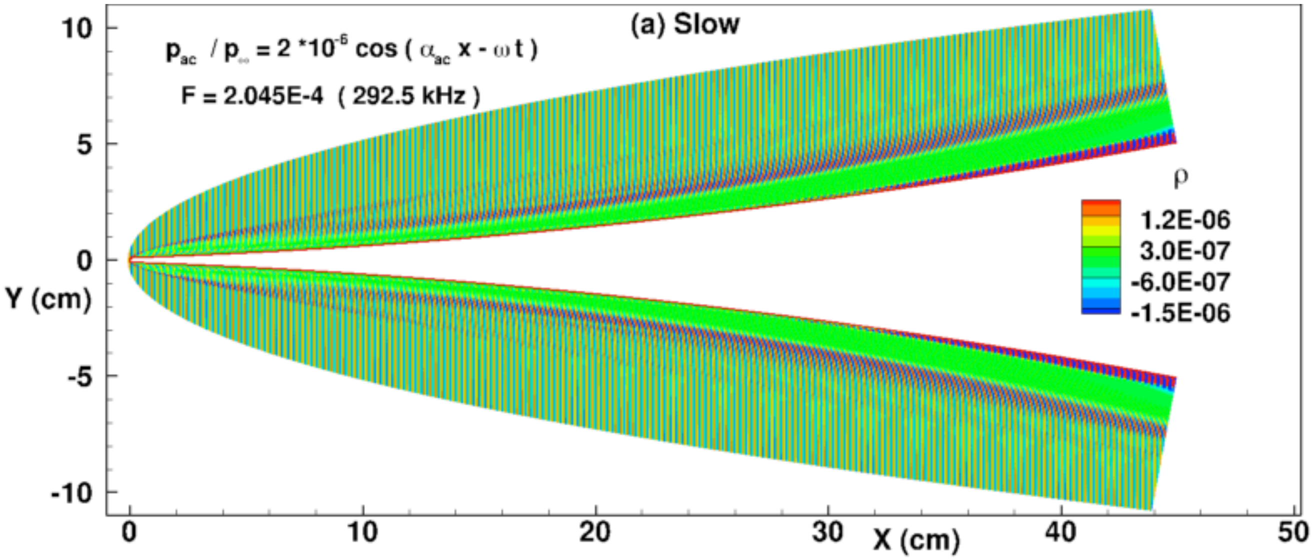
Measured spectrum $(p_{ac})_{PSD} = C \quad f^{-3.5} / Hz$

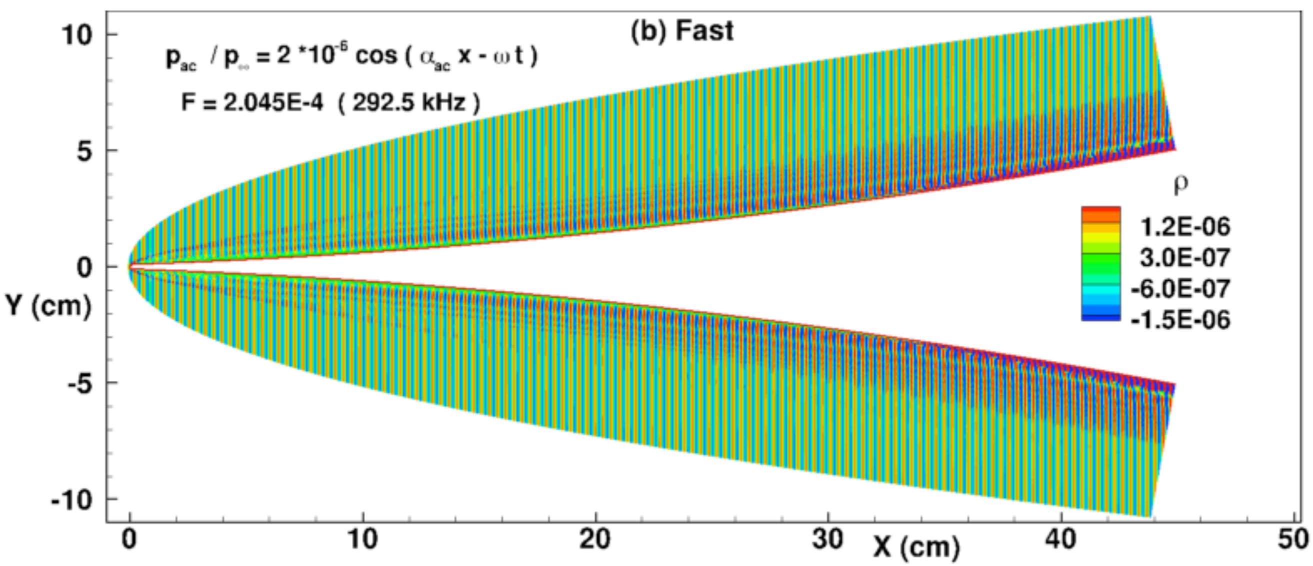
$$2\left(\tilde{p}_{ac}\right)^2 = C \quad f^{-3.5}\,\Delta f$$

$\Delta f \sim 10 \quad to\ \ 100\ kHz$ **(need to investigate more)**

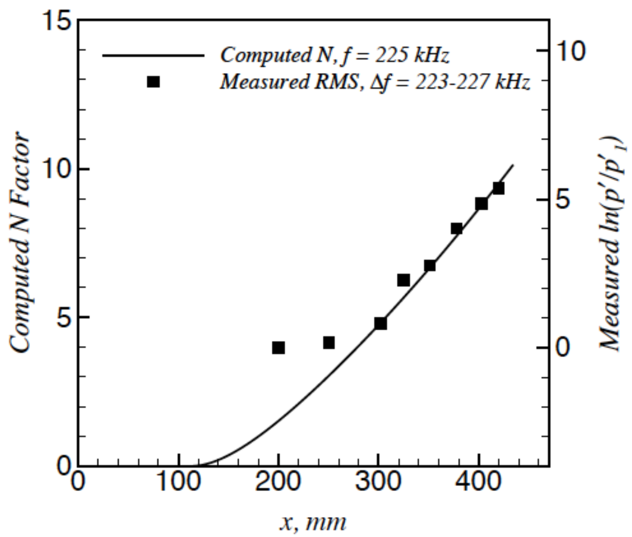
Fig. 18 PSD from expt. (Marineu et al. AIAA 2015)

DNS (Flared-Blunt-Cone)

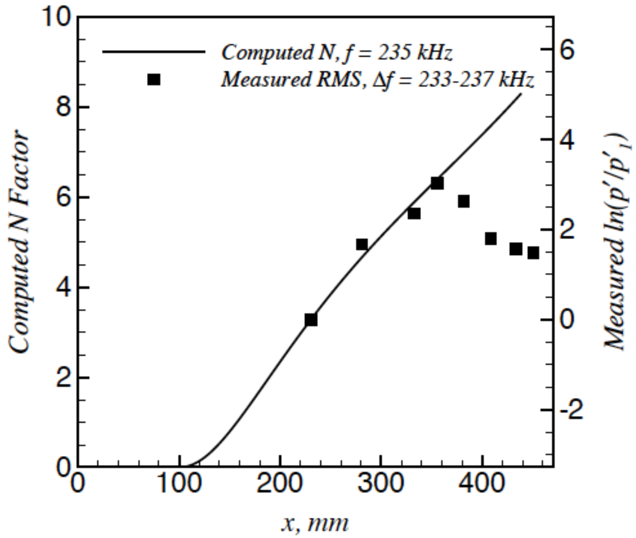




Expts. (Flared-Blunt and –Sharp Cones)

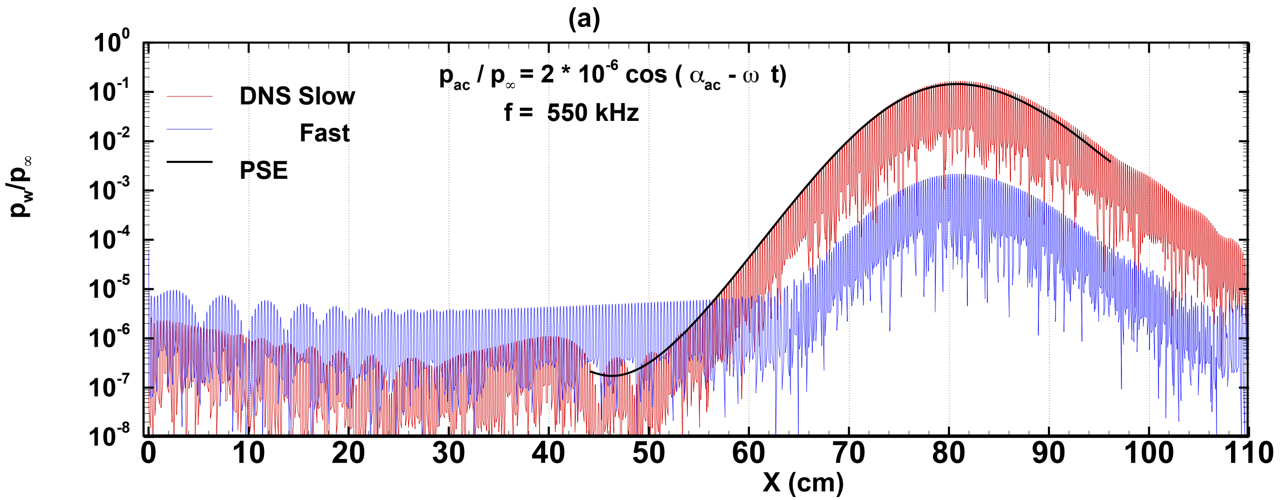


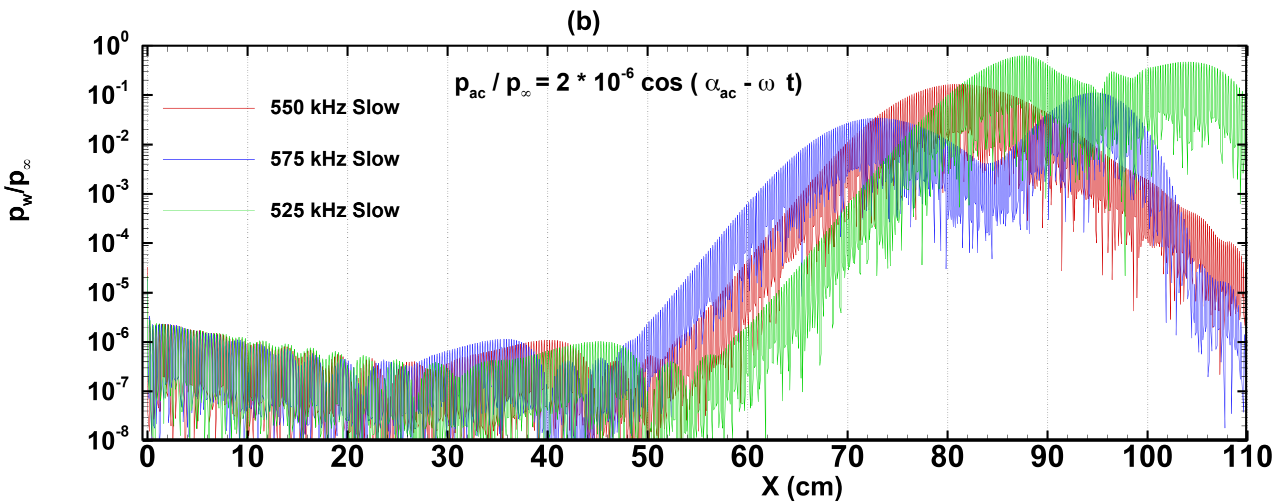
(a) $r_n = 1$ mm. Computation: $p_0 = 600$ kPa, $T_0 = 411$ K, $\rho_\infty = 0.026\ \mathrm{kg/m^3}$. Experiment: $p_0 = 605.5$ kPa, $T_0 = 412.3$ K, $\rho_\infty = 0.026\ \mathrm{kg/m^3}$.



(b) $r_n = 0.16$ mm. Computation: $p_0 = 535$ kPa, $T_0 = 428$ K, $\rho_\infty = 0.023\ \mathrm{kg/m^3}$. Experiment: $p_0 = 537.6$ kPa, $T_0 = 429.0$ K, $\rho_\infty = 0.023\ \mathrm{kg/m^3}$.

DNS (HIFiRE-1)


(a)
$p_{ac} / p_\infty = 2 * 10^{-6} \cos (\alpha_{ac} - \omega\ t)$
f = 550 kHz
DNS Slow
Fast
PSE
p_w/p_∞
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
10
20
30
40
50
60
70
80
90
100
110
X (cm)


(b)
$p_{ac} / p_\infty = 2 * 10^{-6} \cos (\alpha_{ac} - \omega\ t)$
550 kHz Slow
575 kHz Slow
525 kHz Slow
p_w/p_∞
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
10
20
30
40
50
60
70
80
90
100
110
X (cm)